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ABSTRACT

We consider the production of an extra $U(1)$ gauge boson (Z_2)(at the SSC) and its decay to a pair of zinos. The subsequent decays of these zinos will give rise to four charged leptons with high p_t, and will be an interesting signal for supersymmetry.

INTRODUCTION

The standard $SU(2) \times U(1)$ gauge theory of the weak and electromagnetic interactions[1-3] is in excellent agreement with the observed properties of the W and the Z bosons, and with all the existing neutral current experiments. However, the possibility that the symmetry group is larger, such as having an extra $U(1)$ at the 100 GeV or higher energy scale, is not excluded by the available dta. The possibility of the existence of such an extra $U(1)$ is indicated by the recent developments in the superstring theories. The mass scale, at which this extra $U(1)$ is broken, is not given by the theory. We shall assume that this extra $U(1)$ remains unbroken all the way down to the weak scale, and thus there is an extra gauge boson, Z_2, with mass of the order of the weak scale. Recently, a number of groups [4-12] have worked out the phenomenological consequences of such an extra gauge boson on the neutral current experiments, the W and Z masses, and its searches in collider experiments. The typical bound on the Z_2 mass is that it can be as low as around 150 GeV. We shall assume that the Z_2 mass is small enough (a few hundred GeV to a few TeV) so that it can be produced at the SSC.

The object of this work is to explore the possibility of discovering supersymmetry at the SSC (if it is not already found at the TEVATRON or LEP) using the supersymmetric decay modes of this new gauge boson, Z_2. In particular, we consider the decays of Z_2

into two zinos, and the subsequent decays of the zinos into the charged leptons and the photinos.

In recent works,[13–16] it was shown that the decay $Z_2 \to Z_1 + H$ has a substantial branching ratio (typically a few percent). The decay $Z_2 \to \widetilde{Z}_i\widetilde{Z}_j$ is a supersymmetric counterpart of the above decay; and is also expected to be a substantial branching fraction. The four charged leptons with large P_T in the final state (along with the missing photinos) will be an interesting signal for supersymmetry. We shall also briefly discuss the background to the signal coming from the $t\bar{t}$ production and their subsequent decays to charged leptons. Though our considerations are valid for any general extra $U(1)$, for the calculations of the cross-sections and the branching ratios, we shall use the $U(1)$ that arises in the superstring E_6 theories. We divide this report as follows. In section 2, we consider the extra gauge boson that arises in E_6 models and its production cross-sections at the SSC. Section 3 contains the discussion of the neutral zino mass matrix, and the calculations of the $Z_2 \to \widetilde{Z}_i\widetilde{Z}_j$ branching ratios. In section 4, we consider the four charged lepton signal, and compare it with the background coming from $t\bar{t}$ production and their subsequent decays. Section 5 contains our conclusions.

2. $PP \to Z_2X$ CROSS-SECTIONS

In E_6 models, of current interest because of superstrings, there are two extra gauge bosons, called Z_ψ and Z_χ. Z_ψ arise when E_6 breaks down to an $SO(10) \times U(1)$ and Z_χ arises when $SO(10)$ breaks down to $SU(5) \times U(1)$. We assume that the lowest lying "extra Z" is an arbitrary mixture of Z_ψ and Z_χ.

$$Z(\alpha) = Z_\psi \cos\alpha + Z_\chi \sin\alpha \tag{1}$$

where α is a mixing angle which specifies a model. The values of $\alpha = 0^0, 90^0$ correspond to pure Z_ψ, Z_χ. The extra Z boson, Z_η that appears in the superstring E_6 corresponds to $\tan\alpha = \sqrt{3/5}$ or $\alpha = 37.8^0$. The coupling constant, g'' of this extra $U(1)$ group, corresponding to any $Z(\alpha)$ is

$$g'' = \sqrt{\frac{5}{3}}g' = \sqrt{\frac{5}{3}}\frac{e}{\cos\theta_W} \tag{2}$$

The Lagrangian for the interaction of the fermions (quarks or leptons) with $Z(\alpha)$ is

$$\mathcal{L} = e\bar{f}\gamma^\mu(g_V + g_A\gamma_5)fZ_\mu(\alpha) \tag{3}$$

Where $f = q$ or l, and e is the electric charge. The values of the coupling constants g_V and g_A are given in table 1. The quantities A and B appearing in table 1 are

$$A \equiv \sqrt{\frac{5}{72}}\ \frac{\cos\alpha}{\cos\theta_W}, \quad B \equiv \frac{\sin\alpha}{2\sqrt{6}\cos\theta_W} \tag{4}$$

Note that in writing the values of the couplings in table 1, we have ignored the small mixing of the $Z(\alpha)$, with the ordinary Z-boson (the so called $Z - Z'$ mixing).

The cross-sections for the process $PP \to Z(\alpha)X$ at the SSC ($\sqrt{s} = 40$ TeV) is given in table 2. For a given mass of $Z(\alpha)$, the cross-section varies roughly by a factor of 2 as α is varied. The numbers quoted represent the top of the band.

3. BRANCHING RATIOS FOR $Z_2 \to \widetilde{Z}_i\widetilde{Z}_j$ DECAYS

In this section, we specify the Higgs sector of the theory, and consider the neutral gaugino mass matrix. The low energy gauge group is $SU(2) \times U(1) \times U'(1)$ with the current eigenstates neutral gauge bosons (coupling constants) given by $A_3(g), B(g')$ and $Z'(g''$ respectively. For the Higgs fields, we take two doublets $H, \overline{H}$ and one singlet, N belonging to the $\underset{\sim}{27}$ representation of E_6. H and $\overline{H}$ are the Higgs doublets with the conventional Higgs quantum numbers, and N is the $SO(10)$ singlet. To be specific, we restrict ourself to the case where the extra gauge group, $U'(1)$ belongs to the superstring $E_6(i.e. U_\eta(1))$. In that case, the hypercharges $Y, \overline{Y}$ and Y_N of $H, \overline{H}$ and N respectively are given by

$$Y = -4/2\sqrt{15}, \overline{Y} = -1/2\sqrt{15}, Y_N = 5/2\sqrt{15} \tag{5}$$

There will be mixing between the neutral gauginos $(\widetilde{A}_3, \widetilde{B}, \widetilde{Z}')$ and the neutral Higgsinos $(\widetilde{H}_0, \widetilde{\overline{H}}_0, \widetilde{N}$. The 6×6 neutral neutral fermion mass matrix in the basis $(\widetilde{A}_3, \widetilde{B}, \widetilde{Z}', \widetilde{H}_0, \widetilde{\overline{H}}_0, \widetilde{N})$ is

$$\begin{pmatrix} m_2 & 0 & 0 & -\frac{g}{\sqrt{2}}V & \frac{g}{\sqrt{2}}\overline{V} & 0 \\ 0 & m_1 & 0 & \frac{g'}{\sqrt{2}}V & -\frac{g'}{\sqrt{2}}\overline{V} & 0 \\ 0 & 0 & m' & -\sqrt{\frac{8}{15}}g''V & -\frac{g''\overline{V}}{\sqrt{30}} & \sqrt{\frac{5}{6}}g''X \\ \frac{-g}{\sqrt{2}}V & \frac{g'}{\sqrt{2}}V & -\sqrt{\frac{8}{15}}g''V & 0 & \lambda X & \lambda\overline{V} \\ \frac{-g}{\sqrt{2}}\overline{V} & -\frac{g'}{\sqrt{2}}\overline{V} & -\frac{g''\overline{V}}{\sqrt{30}} & \lambda X & 0 & \lambda V \\ 0 & 0 & \sqrt{\frac{5}{6}}g''X & \lambda\overline{V} & \lambda V & 0 \end{pmatrix} \tag{6}$$

Where V, and $\overline{V}$ and X the vacuum expectation values (VEVs) of H, $\overline{H}$ and N respectively. m_1, m_2 and m' are the tree level gaugino masses, and λ is the $H\overline{H}N$ trilinear coupling. The 6×6 mass matrix has to be diagonalized numerically. However, in the limit of $(m_1, m_2, m', V, \overline{V}) << X$, the mass eigenvalues are (we assume m_1, m_2, m', V and $\overline{V}$ are of the same order $\sim V$)

$$\begin{aligned}
M_{\widetilde{\gamma},\widetilde{Z}_1} &= 0(V) \\
M_{\widetilde{Z}_2,\widetilde{Z}_3} &= \pm\lambda X\left[1+0\left(\frac{V}{X}\right)\right] \\
M_{\widetilde{Z}_4,\widetilde{Z}_5} &= \pm\beta X\left[1+0\left(\frac{V}{X}\right)\right]
\end{aligned} \tag{7}$$

$$\text{where} \quad \beta \equiv \sqrt{\frac{5}{6}} g''$$

The interactions between the Z_1 and Z_2 gauge boson mass eigenstates and the gaugino mass eigenstates $(\widetilde{\gamma}, \widetilde{Z}_i, i = 1-5)$ can be written as

$$\mathcal{L}_{Z_a\widetilde{Z}_i\widetilde{Z}_j} = e g_{Z_a\widetilde{Z}_i\widetilde{Z}_j} \overline{\widetilde{Z}}_i \gamma^\mu \gamma_5 \widetilde{Z}_j Z_{a\mu} \tag{8}$$

where $a = 1, 2$. In the above approximations, the coupling constants with the lightest zino, $\widetilde{Z}_1$ are obtained to be

$$\begin{aligned}
g_{Z_1\widetilde{Z}_1\widetilde{Z}_1} &= 0(r^3) \\
g_{Z_2\widetilde{Z}_1\widetilde{Z}_1} &= -\frac{1}{2\cos\theta_W}\; 0(r^2) \simeq -\frac{1}{2\cos\theta_W}\; 0\left(\frac{M_{Z_1}}{M_{Z_2}}\right)^2
\end{aligned} \tag{9}$$

$g_{Z_1\widetilde{Z}_i\widetilde{Z}_i}$ coupling is zero to order r^2, because the hypercharges of H and $\overline{H}$ are equal and opposite with respect to the usual $U(1)$, and their contributions cancel. However, this is not true for the extra $U(1)$ (see Eq.(5)). The total decay width of Z_2 for decays to 3 families of fermions (allowing decays to only 15 ordinary fermions in a family) is given by

$$\Gamma_2 = \frac{5\alpha_{em}}{8\ \cos^2\theta_W} M_2 \tag{10}$$

Eq. (10) is for the case of the superstring E_6, $\tan\alpha = \sqrt{\frac{3}{5}}$. Using Eqs. (8),(9) and (10), we obtain the branching ratio

$$B(Z_2 \to \widetilde{Z}_1\widetilde{Z}_1) = \frac{8}{15} g^2_{Z_2\widetilde{Z}_1\widetilde{Z}_1} \cos^2\theta_W \left[1 - \frac{4\widetilde{M}^2}{M_2^2}\right]^{3/2} . \tag{11}$$

Using $g_{Z_2\widetilde{Z}_1\widetilde{Z}_1} = \left(\frac{M_{Z_1}}{M_{Z_2}}\right)^2 \frac{1}{\cos\theta_W}$, $M_2 = 200$ GeV, $\widetilde{M} = 50$ GeV, we obtain $B(Z_2 \to \widetilde{Z}_1\widetilde{Z}_1) \simeq 0.02$. Thus, for a low mass Z_2, a few percent branching ratio is likley, and it will decrease with the increase of M_2.

4. MULTILEPTON SIGNAL

We now consider 4 charged lepton signal coming from

$$PP \to Z_2 X \to \tilde{Z}_1 \tilde{Z}_1 X \to (l_1^+ l_1^- \tilde{\gamma}) + (l_2^+ l_2^- \tilde{\gamma}) + X \tag{12}$$

where $l = e$ or μ.

The branching ratio for the $\tilde{Z}_1 \to l^+ l^- \tilde{\gamma}$ is $\sim 0.11 \times 2 \simeq 0.22$, counting both e and μ. Using Eq.(11) for $B(Z_2 \to \widetilde{Z}_1 \widetilde{Z}_1$ and $g_{Z_2 \tilde{Z}_1 \tilde{Z}_1} \simeq (\frac{M_1}{M_2})^2 \frac{1}{\cos\theta_W}$, the values of the $\sigma \cdot B$ for $PP \to Z_2 X \to \widetilde{Z}_1 \widetilde{Z}_1 X$, and $PP \to Z_2 X \to \widetilde{Z}_1 \widetilde{Z}_1 X \to (l^+ l^- \tilde{\gamma})(l^+ l^- \tilde{\gamma}) X$ is given in table 2. With an annual luminosity, $\int \mathcal{L} dt = 10^4 pb^{-1}$, we find the signal is sizable. For example, for $M_2 = 200$ GeV, we expect 10^5 events/yr. with four charged leptons in the final state.

We now briefly discuss the background coming from the production of $t\bar{t}$ and their subsequent semileptonic decays.

$$PP \to t\bar{t}X \to (l_1^+ + \nu_1 + l_2^- + \bar{\nu}_2 + c) + (l_2^- + \bar{\nu}_3 + l_4^+ + \nu_4 + \bar{c}) + X \tag{13}$$

Because one more decay chain is involved, we expect the final state charged leptons here to carry much less p_T on the average. So, with suitable P_T - cuts, it may be possible to eliminate most of the background events.[17–18)] In table 3, we give an estimate of $t\bar{t}$ production cross-sections and $\sigma B(t\bar{t} \to l^+ l^- l^+ l^- \nu\nu\bar{\nu}\bar{\nu})$ with $B \sim 10^{-3}$. We have not used any P_T cut in this estimate. We also point out that the direct production[17] cross-section $PP \to \widetilde{Z}_1 \widetilde{Z}_1 X$ is much smaller than that via Z_2, because of the resonance benefit of Z_2.

5. CONCLUSIONS

1. The cross-section for $PP \to Z_2 X \to \widetilde{Z}_1 \widetilde{Z}_1 X$ is much bigger than the direct production[17)] $PP \to \widetilde{Z}_1 \widetilde{Z}_1 X$, because of the resonance benefit of Z_2.

2. Branching ratio for $Z_2 \to \widetilde{Z}_1 \widetilde{Z}_1$ can be as large as a few percent. For $M_{Z_2} =$ 200 GeV, $\widetilde{M_{Z_1}} = 50$ GeV, $B \simeq 0 \cdot 02$

3. σB for the four charged leptons in the final state is sizable. For $M_{Z_2} = 200$ GeV, we expect about 10^5 events per year at SSC. However, number of events decreases rapidly as M_{Z_2} increases (table 2).

4. Top background is large, but can be eliminated using suitable cuts.[17,18)] For a very light $Z_2(M_{Z_2} = 200 - 300$ GeV), and very heavy top quark, ($M_t \geq 150$ GeV), the signal and the back ground are comparable even without any P_T cut (table 2 and 3).

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[17] A more detail discussion of this material is given in the report by R. Arnowitt to this proceedings.

[18] A more detail discussion of this material is given in the report by R. Arnowitt, R. M. Barnett, P. Nath and F. Parge to this proceedings.

TABLE 1: Couplings of the Fermions to the extra gauge boson Z_α

FERMIONS	g_V	g_A
u	0	A + B
d	-2B	A - B
e	2B	A - B
ν	$\frac{1}{2}$(A - 3B)	$-\frac{1}{2}$(A - 3B)

TABLE 2: Multilepton signal from Z_2

M_{Z_2} (TeV)	σ_{Z_2+X} (pb)	$\frac{\sigma B(\tilde{Z}_1 \tilde{Z}_1 X)}{(pb)}$	$\frac{\sigma B(\ell^+\ell^-\tilde{\gamma}+\ell^+\ell^-\tilde{\gamma}X)}{(pb)}$
.2	10^4	160	8
.3	5×10^3	20	1
.4	10^3	1.4	7×10^{-2}
.5	500	0.3	1.4×10^{-2}
.6	400	0.1	5×10^{-3}
.8	100	9×10^{-3}	4×10^{-4}
1.0	50	1.9×10^{-3}	9×10^{-5}
1.5	8	6×10^{-5}	3×10^{-6}
2.0	2	5×10^{-6}	2×10^{-7}

TABLE 3: Multilepton background from $t\bar{t}$.

m_t (GeV)	$\sigma_{t\bar{t}X}$ (nb)	$\dfrac{\sigma_{t\bar{t}} B(\ell^+\ell^-\ell^+\ell^-\nu's X)}{(\text{pb})}$
50	600	600
100	40	40
150	8	8
200	3	3
250	1	1
300	0.5	0.5